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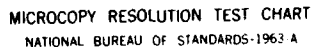
PROTECTIVE VERTICAL SHELTERS(U) BALLISTIC MISSILE
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PHYSICAL MODELING TECHNIQUES FOR MISSILE
AND OTHER
PROTECTIVE STRUCTURES

Papers Submitted for Presentation During the
American Society of Civil Engineers
National Spring Convention
Las Vegas, April 1982

Sponsored By the ASCE Engineering Mechanics Division
Committee on Experimental Analysis and Instrumentation

Edited By: T. Krauthammer and C. D. Sutton

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29 Jun 83

SUBJECT

Review of Material for Public Release

TO

Mr. James Shafer
Defense Technical Information Center
DDAC
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The following technical papers have been reviewed by our office and are approved for public release. This headquarters has no objection to their public release and authorizes publication.

1. (BMO 81-296) ⁴¹¹⁵⁹⁴ "Protective Vertical Shelters" by Ian Narain, A.M. ASCE, Jerry Stepheno, A.M. ASCE, and Gary Landon, A.M. ASCE.
2. (BMO 82-020) "Dynamic Cylinder Test Program" by Jerry Stephens, A.M. ASCE.
3. (AFCMD/82-018) ⁴⁰⁶⁷⁷⁶ "Blast and Shock Field Test Management" by Michael Noble.
4. (AFCMD/82-014) "A Comparison of Nuclear Simulation Techniques on Generic MX Structures" by John Betz.
5. (AFCMD/82-013) "Finite Element Dynamic Analysis of the DCT-2 Models" by Barry Bingham.
6. (AFCMD/82-017) "MX Basing Development Derived From H. E. Testing" by Donald Cole.
7. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Experimental Program" by J. I. Daniel and D. M. Schultz.
8. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Specimen Construction" by A. T. Ciolko.
9. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Instrumentation and Load Control" by M. W. Hanson and J. T. Julien.
10. (BMO 82-003) "Laboratory Investigation of Expansion, Venting, and Shock Attenuation in the MX Trench" by J. K. Gran, J. R. Bruce, and J. D. Colton.

11. (BMO 82-003) "Small-Scale Tests of MX Vertical Shelter Structures" by J. K. Gran, J. R. Bruce, and J. D. Colton.

12. (BMO 82-001) "Determination of Soil Properties Through Ground Motion Analysis" by John Frye and Norman Lipner.

13. (BMO 82-062) "Instrumentation for Protective Structures Testing" by Joe Quintana.

14. (BMO 82-105) "1/5 Size VHS Series Blast and Shock Simulations" by Michael Noble.

15. (BMO 82-126) "The Use of Physical Models in Development of the MX Protective Shelter" by Eugene Sevin.

*16. REJECTED: (BMO 82-029) "Survey of Experimental Work on the Dynamic Behavior of Concrete Structures in the USSR" by Leonid Millstein and Gajanen Sabnis.

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PROTECTIVE VERTICAL SHELTERS

by

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INTRODUCTION

This paper describes the test program entitled GOVS (Giant Reusable Airblast Simulator (GRABS) on Vertical Shelters) which was an investigation of the response of vertical shelters for Missile-X (MX) to vertical airblast and to airblast-induced ground-shock loadings. Specifically under investigation in these tests were the effects of site geology (depth to bedrock) and structural detail (presence of a shelter transition section, thickness-to-radius ratio (t/r) of the shelter tube section, and concrete strength) on shelter response. In addition, the results of these tests were used to evaluate analytical computer procedures, to correlate static and dynamic test data, and to provide information for research relating to shock isolation systems (SIS).

The GOVS program consisted of three tests conducted on models one-sixth the size of a generic vertical shelter. The models were constructed, instrumented, and dynamically tested by the New Mexico Engineering Research Institute (NMERI) at the Eric H. Wang Civil Engineering Research Facility (CERF) on Kirtland Air Force Base (KAFB), Albuquerque, New Mexico. One

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model of shelter configuration A and two models of shelter configuration B were tested individually in the GRABS facility at CERF (see Figure 1).

The test-bed for each test was composed of dry sand rained into place at a uniform density around the test structure. Model instrumentation included blast-pressure gages, accelerometers, velocity gages, strain gages, structure-media interaction (SMI) gages, interface-pressure gages, and relative-displacement gages. Test-bed instrumentation consisted of blast-pressure, soil-stress, and acceleration gages.

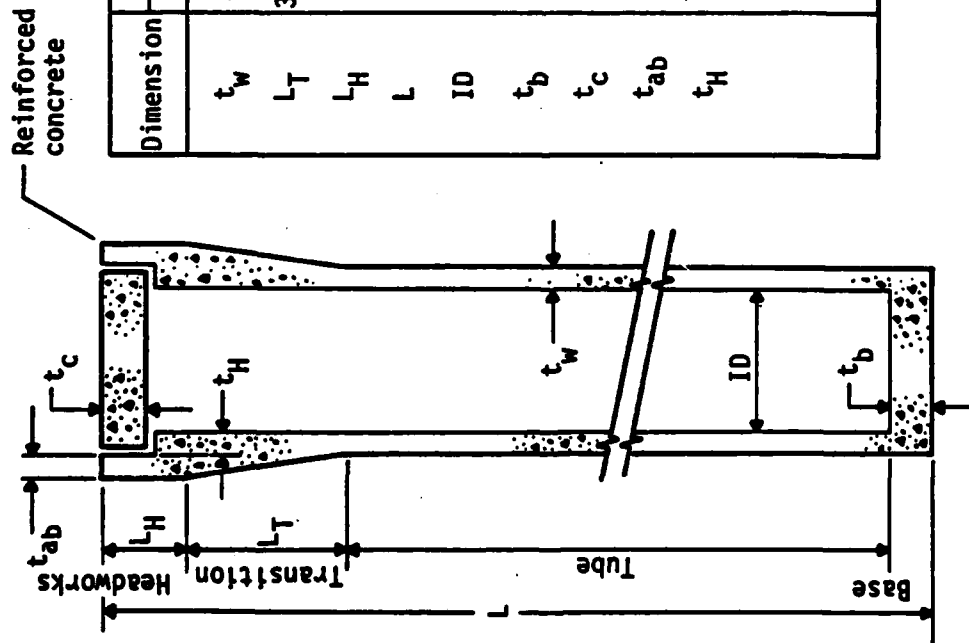
The design environment for GOVS-1 consisted of a vertical airblast with a peak overpressure of 8.3 MPa and a scaled yield of 23 kt (scaled ^(1700 ps) 5 Mt). The design environments for GOVS-2 and GOVS-3 were the same as the actual GOVS-1 test environment. This environment was generated by the High-Explosives Simulation Technique (HEST). Three calibration tests were conducted in the GRABS facility to define the HEST structure for the GOVS tests.

A SAMSON dynamic finite-element computer code provided pretest predictions of stresses and motions within both the structure and the free-field. The code generated acceleration, velocity, displacement, and stress and strain histories for the structure and the soil. An axisymmetric model of the test layout was assumed. The structure and test-bed materials were modeled in the calculation as piecewise linear, elastic-plastic materials.

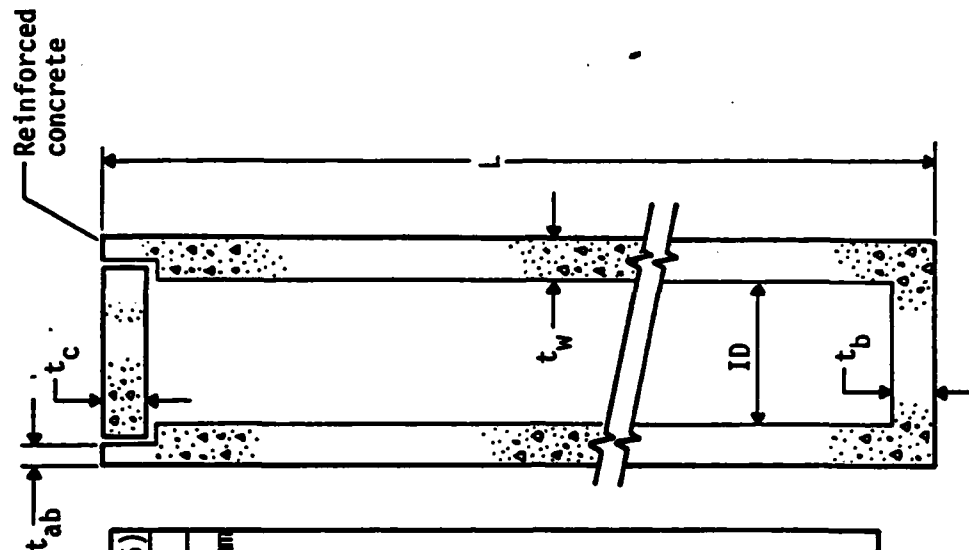
TEST DESCRIPTION

Shelter Models

The generic MX vertical shelter is basically a large, reinforced-concrete canister capped with a removable closure. The specific



Configuration A



Configuration B

Dimension	Full size		Model (1/5.85)	
	A	B	A	B
t_w	305 mm	610 mm	51 mm	102 mm
L_T	3048 mm	—	521 mm	—
L_H	1524 mm	—	261 mm	—
L	38.35 m	—	6.56 m	—
ID	4.27 m	—	730 mm	—
t_b	838 mm	—	143 mm	—
t_c	1016 mm	—	174 mm	—
t_{ab}	305 mm	—	51 mm	—
t_H	305 mm	—	51 mm	—

configurations of vertical shelter types A and B are shown in Figure 1. Both the full-size shelter dimensions and the corresponding model dimensions are indicated on this figure. The model dimensions were scaled from the full-size dimensions by a factor of 1/5.85, rather than 1/6, so that commercially available form material could be used in the construction of the model. The geometry of the closure, headworks, and base was identical for both shelter configurations. The tube in shelter A, however, had a full-size wall thickness of 305 mm in comparison to the 610-mm tube wall thickness for full-size shelter B. The reduction of the wall thickness in shelter A was accomplished by means of a transition section placed between the headworks and the tube.

The shelter models were constructed of conventionally reinforced concrete. The concrete in the A and B models had design 28-day unconfined compression strengths of 27.6 MPa and 41.1 MPa, respectively. The mix proportions are reported in Table 1. Type II high-early portland cement was used in the mixes. The maximum size of the aggregate in the concrete was 6.4 mm.

The percentages of steel reinforcement used in the GOVS models are listed in Table 2. The primary reinforcement in the headworks, transition, and tube of model A was D-2.5 deformed wire. The primary reinforcement in the headworks and tube of the B models was No. 2 deformed bars. All model bases were reinforced with No. 4 deformed bars. The stirrups in the models consisted of 2.4-mm-diameter wire for the A model and 3.2-mm-diameter wire for the B models. The tensile yield strengths of the D-2.5 deformed wire, the No. 2 deformed bars, and the No. 4 deformed bars were 483, 480, and 414 MPa, respectively.

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TABLE 1. GOVS CONCRETE MIX PROPORTIONS (PER YARDS)

Content	Model A	Models B1 and B2 and all Closures
Cement, in kilograms	299	342
Fine aggregate, in kilograms	927	795
Coarse (6.4-millimeters) aggregate, in kilograms	245	532
Water, in kilograms	189	155
Pozzoligh, in milliliters	1183	1124
Entrained air, as a percentage	3	3
Slump, in millimeters	127	127
Water/cement ratio	0.63	0.45

TABLE 2. MODEL REINFORCEMENT PERCENTAGES

Model	Longitudinal Steel, as a Percentage of Volume	Hoop Steel, as a Percentage of Volume	Radial Steel, as a Percentage of Volume
	GOVS	GOVS	GOVS
A			
Headworks	0.94	0.50	0.12
Transition	0.98	0.99	0.13
Tube	1.03	1.00	0.11
B			
Headworks	0.97	0.50	----
Tube	0.97	1.00	0.19

The structure closures, identical for all three models, were reinforced with No. 4 bars. The concrete used in the closures had a 28-day unconfined compression strength of 41.4 MPa. The shells and liners were studded with 6.44-mm-diameter Nelson studs. In each model, the closure was anchored with eight 12.7-mm-diameter A325 bolts (tensile ultimate strength of 828 MPa) to a steel ring welded to the headworks liner. A pressure penetration seal, which consisted of a 51-mm-wide by 3.3-mm-thick circular plate, was welded to the closure liners.

MODEL FABRICATION

Fabrication of the models was accomplished in three phases, form assembly, constructing the reinforcing cage, and casting and curing the concrete. The vertical shelter models were constructed in an inverted position. The forms for the inside walls were fiber-void tubes. The bottom end of the void tube was anchored against the steel lining of the headworks. Approximately 2 m of sand were placed in the tube for additional support. The upper end of the tube was capped with a plywood disk. The reinforcing cage for each model was fabricated around the completed inside form. All instrumentation leads were routed to the inside of the model.

The outside form was slipped over the assembled reinforcing cage. This form consisted of a steel liner divided longitudinally into five approximately equal segments. The segment-to-segment connections were covered with steel bands. A uniform wall thickness was maintained in the tube section by steel rod spacers placed between the inner and outer forms. Each model was cast in five approximately equal sections from two batches

of concrete. A steel funnel clamped around the tops of the form segments was used to facilitate concrete placement. The concrete was consolidated by four air-driven form vibrators, three attached to the funnel and one attached to the base plate of the model.

When the model had been cast, the exposed concrete surfaces were sprayed with curing compound. The model was allowed to cure for about one week. The outside forms were then stripped, and the model was placed in a horizontal position and was transported to the GRABS facility, where the inside forms were stripped. The models were instrumented at the test site while they were still lying in the horizontal position.

Test specimens were cast from each batch of concrete for material strength and response testing. The sampling and testing program for this concrete is summarized in Table 3. Most of the concrete specimens were molded and cured in the laboratory according to the standards of the American Society for Testing and Materials (ASTM); exceptions are indicated in Table 3. In addition to the tests on the concrete specimens, tensile stress-strain tests and pull-out tests were conducted on each size of reinforcing bar (wire) used in the models.

INSTRUMENTATION

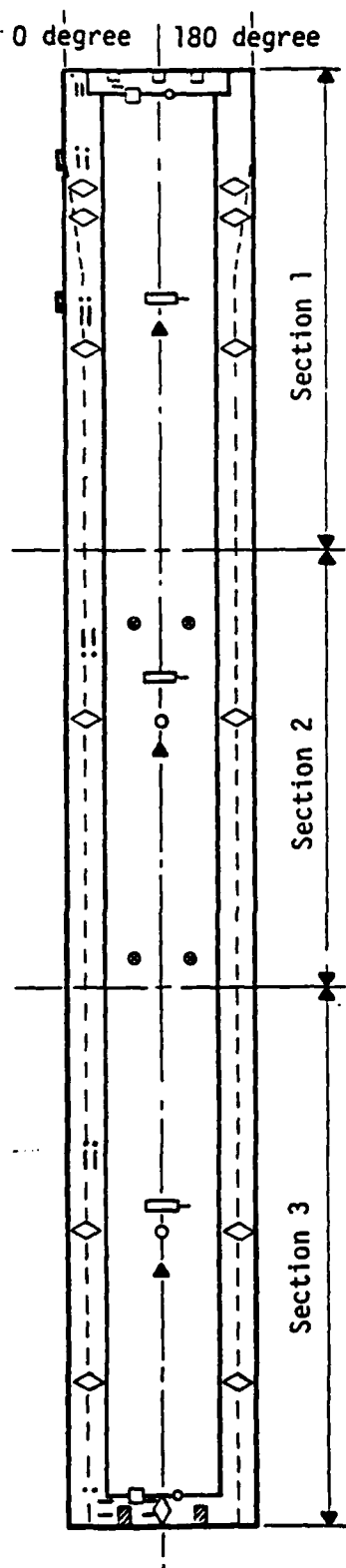
Both electrical (active) and mechanical (passive) measurements were taken during the GOVS events. The electrical gages measured strain, SMI, blast pressure, model motions, free-field motion and stress, interface pressure, and relative model displacement. The mechanical devices measured only relative model displacement. Model and free-field instrumentation locations are given in Figure 2. An average of 163 channels

TABLE 3. GOVS MATERIAL TESTING PROGRAM

Test	ASTM Specification	Specimen Size	Number of Specimens per Batch	Test Schedule	Comments
Concrete slump	C143-74	---	1	---	---
Concrete compressive strength	C 39-72	152- by 305-mm cylinders	32 ^a	4 at 07 days 4 at 14 days 4 at 21 days 4 at 28 days 4 at 35 days 4 at test day	Stress-strain curves for 28-day tests
Concrete flexural strength	C 78-75	152- by 152- by 508-mm beams	6 ^b	2 at 28 days 4 at test day	Load-deflection curves for 28-day tests
Concrete splitting tensile strength	C496-71	152- by 305-mm cylinders	6 ^b	2 at 28 days 4 at test day	---
Reinforcing bar tensile test	---	---	---	---	Four tensile-stress/strain tests for each size of bar

^a Sixteen specimens molded and cured according to ASTM C31-69; sixteen specimens covered and cured with the model. Two cylinders from each curing process tested on the days indicated.

^b All concrete specimens molded and laboratory-cured according to ASTM C31-69 except that two specimens for each test (tested on test day) were covered and cured with the models.

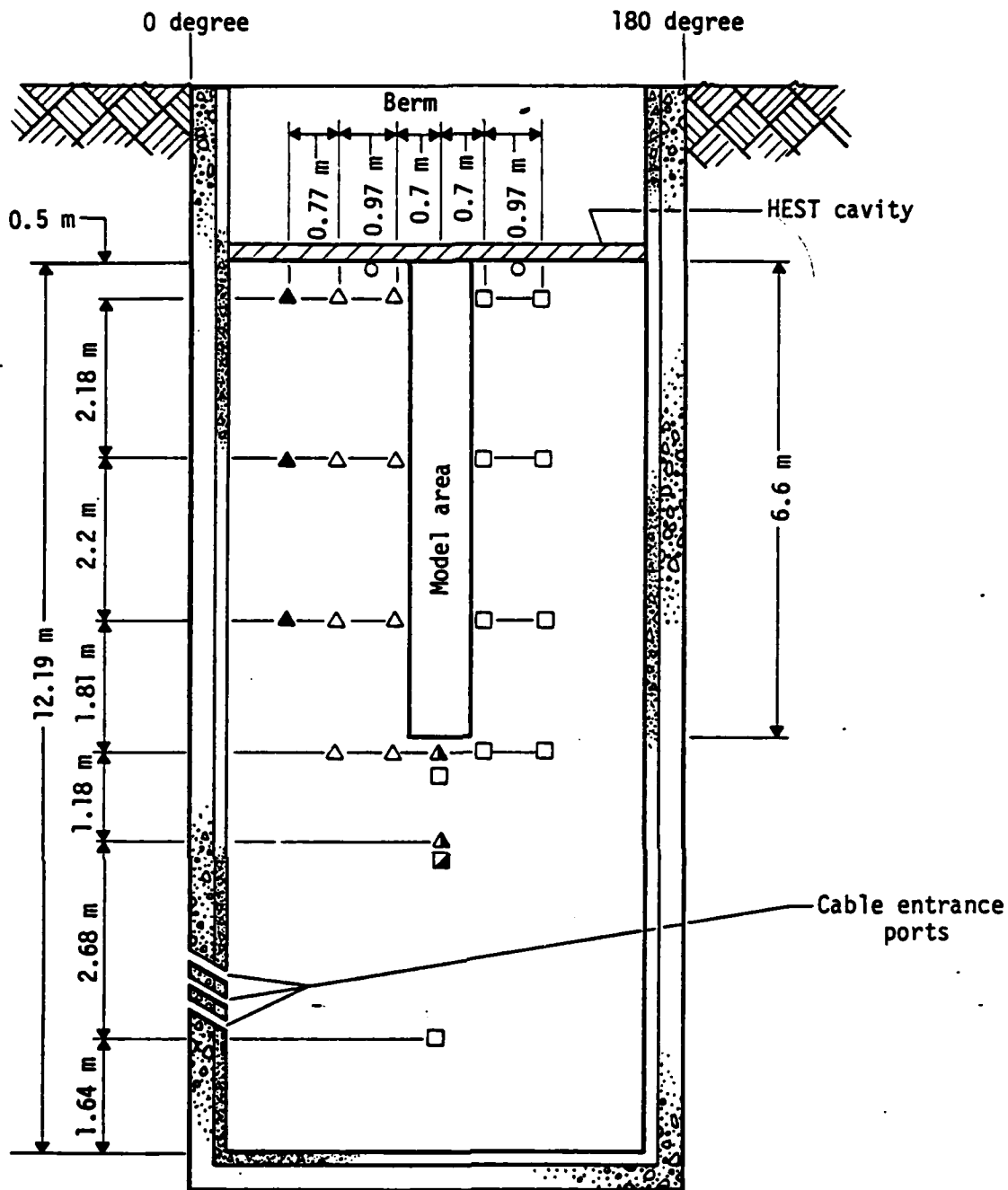


Measurement	Symbol	Number
Blast Pressure (BP)	□	4
Velocity (V)	□	1
Acceleration (A)	○	3
Structure-Media Interaction (SMI)	◇	18
Steel Strain (SE)	or •	28
Concrete Strain (CE)		4
Relative Displacement (RD)		
0-180 degree	□	1
90-270 degree	▲	1

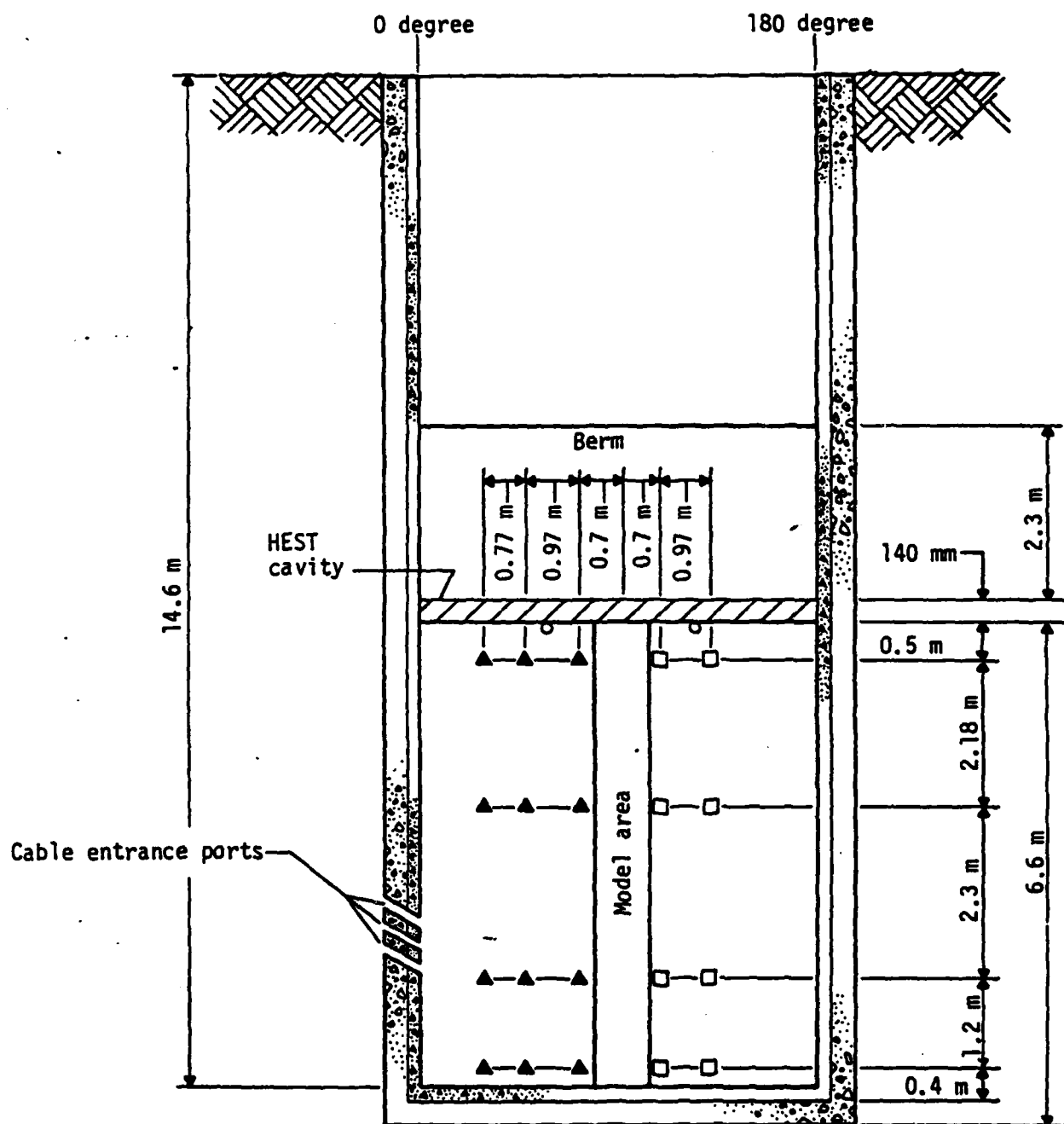
Acceleration (A)	○	2
Structure-Media Interaction (SMI)	◇	6
Steel Strain (SE)	or •	6
Relative Displacement (RD)	□ or ▲	2
Cable Exits	•	4
Concrete Strain (CE)		0

Velocity (V)	□	1
Acceleration (A)	○	5
Structure-Media Interaction (SMI)	◇	13
Steel Strain (SE)	or •	14
Relative Displacement (RD)	□ or ▲	2
Interface Pressure (IP)	▨	4
Concrete Strain (CE)		0

Note: Dotted lines indicate model A structure.



- Blast pressure gage
- Soil stress gage vertical and radial
- Soil stress gage radial
- ▣ Soil stress gage vertical
- △ Soil accelerometer vertical and radial
- ▲ Soil accelerometer radial
- ▲ Soil accelerometer vertical



- Blast pressure gage
- Soil stress gage vertical and radial
- Soil stress gage radial
- ▣ Soil stress gage vertical
- △ Soil accelerometer vertical and radial
- ▲ Soil accelerometer radial
- ▲ Soil accelerometer vertical

was recorded in each test.

Strain measurements were taken on the reinforcing bar (rebar), on the steel liners of the closure and the headworks, and on the faces of each model wall. The closure gages were located where they would indicate flexural behavior, as were the rebar gages in the model base. Vertical gages installed on the longitudinal rebar in the model measured axial and flexural behavior. Gages were placed on the hoop reinforcement to indicate tangential compression and extension modes of behavior.

Blast-pressure measurements were taken in both the model closure and the free-field. Four gages were located in the closure and six in the free-field to ensure adequate pressure-history data and also to check the symmetry and uniformity of the loading. The blast-pressure gages, enclosed in steel canisters, were cast in the concrete during the construction of the closures and were enclosed in 305-mm-diameter by 610-mm-deep concrete canisters for the free-field measurements. All blast-pressure gages were protected with a debris shield.

Velocity gages and accelerometers were used for measuring model motions. Velocity measurements were taken on the bottom of the closure and on the base of the model in the vertical direction with Sandia-type DX velocity gages. Acceleration measurements were also taken on the model closure and base and at two other locations along the length of the tube.

Structure-media interaction measurements were taken electronically with NMERI-built SMI gages and Waterways Experiment Station (WES) Air Force-Modified (WAM) interface pressure gages. The SMI transducer provides a measurement of three mutually orthogonal dynamic stress vector histories, normal stress, horizontal shear stress and tangential shear stress, at the

structure-media interface (Reference 5). The gages were mounted in canisters cast in the model during construction and were located in such a way that normal, vertical, and tangential input loading to the structure could be determined at critical points.

Radial compression and extension of the tube section were measured with active linear potentiometers mounted in parallel on passive scratch gages.

Free-field stress and motion were measured with soil-stress gages (WES type) and accelerometers, respectively. Radial sensing gages were paired with vertical sensing gages at various locations to determine vertical-to-horizontal stress and motion ratios. The soil-stress gages, with vertical sensing axes, were firmly pressed into the test-bed and covered with rained sand. The soil-stress gages, with horizontal or radial sensing axes, were positioned on vertical support wires which were implanted into the test-bed. Soil accelerations were measured with accelerometers mounted in epoxy canisters.

The transducer data were recorded in vans, which were located approximately 150 m from the test facility. The recording equipment used in the GOVS test events is listed in Table 4. The recorded test data were reduced to computer-produced plots by the Air Force Weapons Laboratory (AFWL) Data Processing Division.

TEST FACILITY

The GRABS facility, located on KAFB, consists of a 5.49-m-diameter, 14.63-m-deep reinforced concrete cylinder emplaced in a massive limestone formation. The facility has a 533-mm-thick wall and a 533-mm-thick base;

TABLE 4. GOVS RECORDING EQUIPMENT

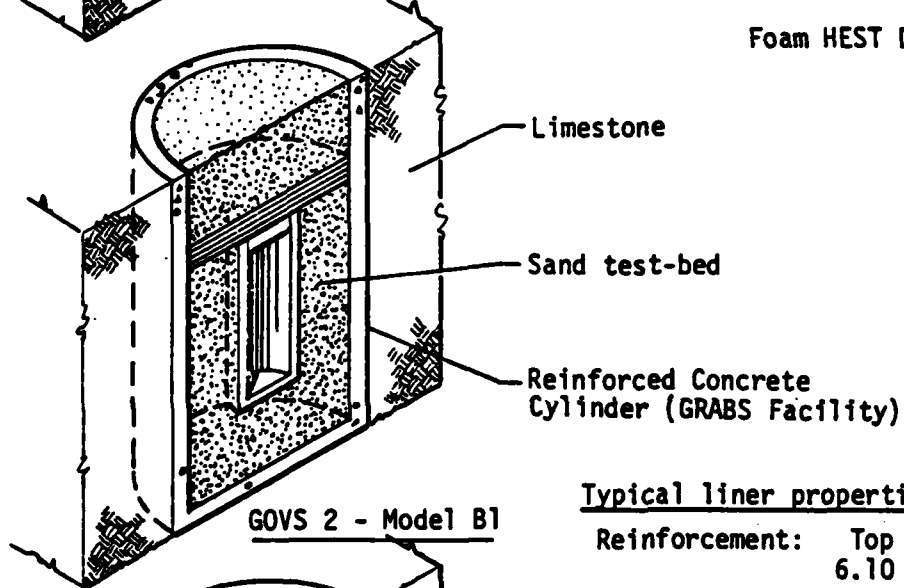
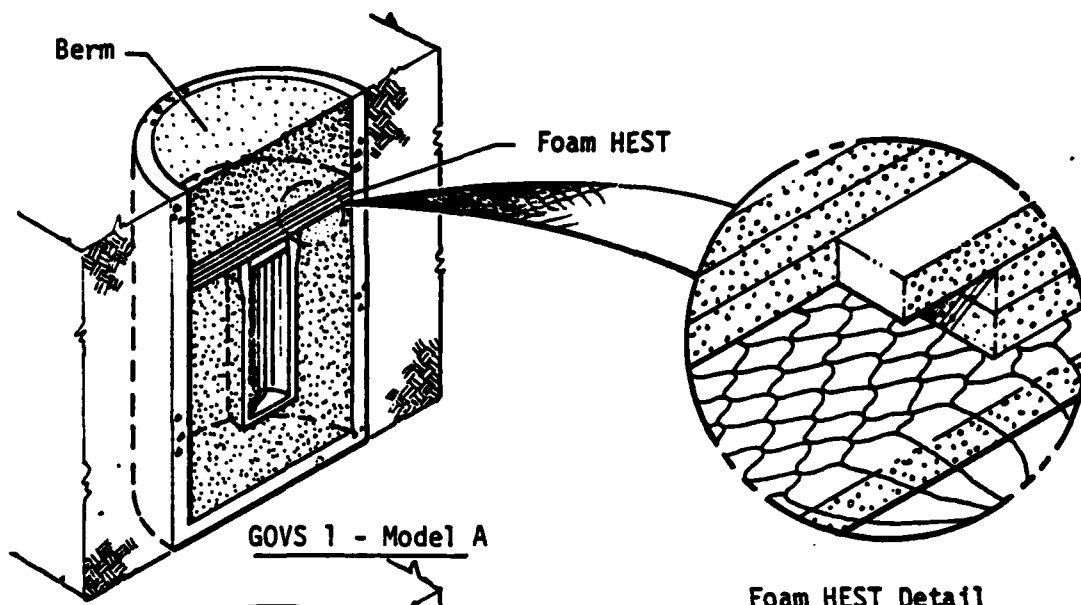
Recording Van	Signal Conditioners	Amplifiers	Recording Equipment	
			Free-field	Model
Van E7	B&F 1-700	B&F 702-10D	BH VR 3700 B, 3300	---
Van 4	B&F 1-234-1	B&F 702-10D	---	BH VR 3700 B Ampex CP 100

both are lined with 6.4-mm-thick steel plate. Construction of the test facility is described in Reference 2. The geometry of the test facility, and the rock properties, is shown in Figure 3. One model of shelter configuration A and two models of shelter configuration B were tested individually in the GRABS facility, also shown in Figure 3.

Before the test-bed material was placed in the facility, the necessary instrumentation cables were pulled through cable entrance holes located near the base of the facility. At the mouth of the access holes the cables were packed in foam to seal the access and isolate the cables from shock. The cables were connected to a junction box at the surface.

The test-bed material was a locally provided, washed and dried concrete sand conforming to ASTM Specification C-33. The sand was placed in the facility by a raining technique. Stockpiled sand was transported by a front-end loader to a hopper that carried sand into the raining device. The device, shown in Figure 4, was rotated around the circumference of the test facility. The flow pattern was controlled by varying the number of holes in the bottom of the device. This system was capable of delivering sand at a rate of approximately $38 \text{ m}^3/\text{h}$.

It has been shown that when sand is rained from the height required for the particles to achieve terminal velocity, a near-maximum uniform density is obtained. Experiments conducted by NMERI have shown that the sand must be rained from a height of at least 610 mm if it is to reach terminal velocity. The height of free-fall for the sand in the GRABS facility ranged from 2.3 m to 14.6 m. Density measurements were taken at 1-m intervals during the test-bed buildup. A Troxler nuclear moisture densitometer with probe depths of 152 mm, 203 mm, and 305 mm was used for



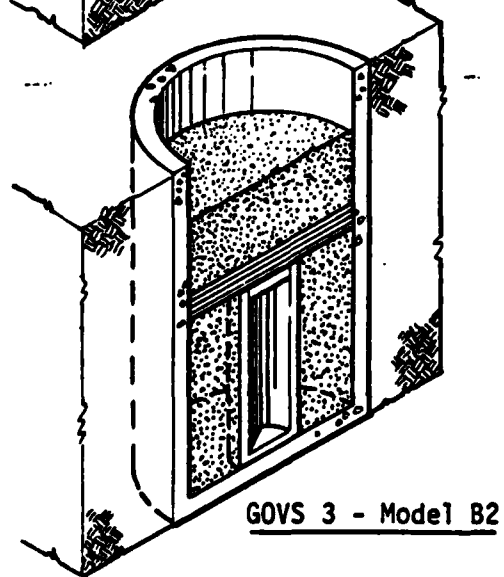
Typical liner properties

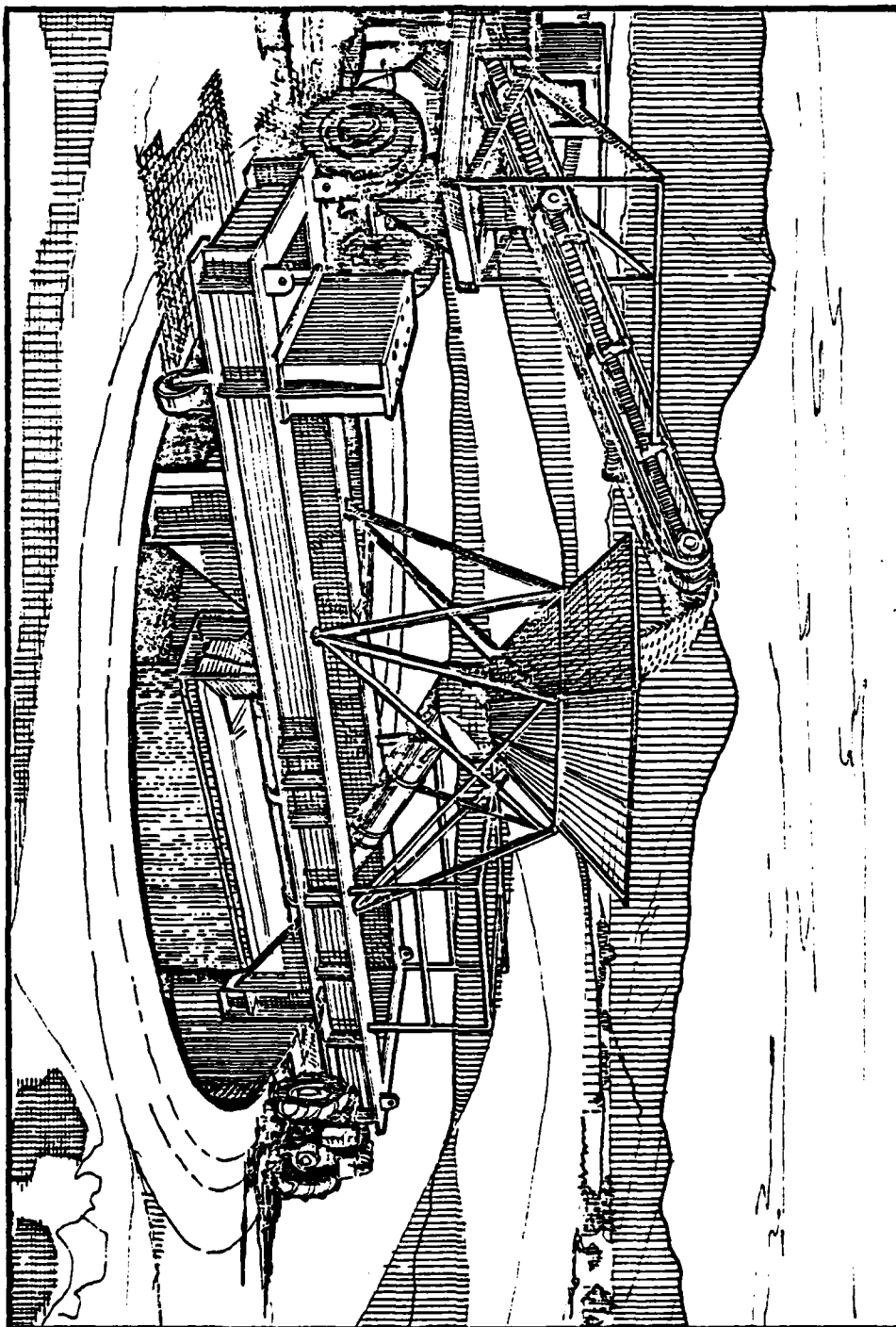
Reinforcement:	Top	Bottom
	6.10 m	8.53 m
Vertical:	1.00%	0.25%
Hoop:	4.50%	2.00%

Steel plate liner: 6.4 mm thick

Assumed rock properties

E = 5170 MPa
No tensile capability





this purpose. The average test-bed unit density was 1746 kg/m^3 .

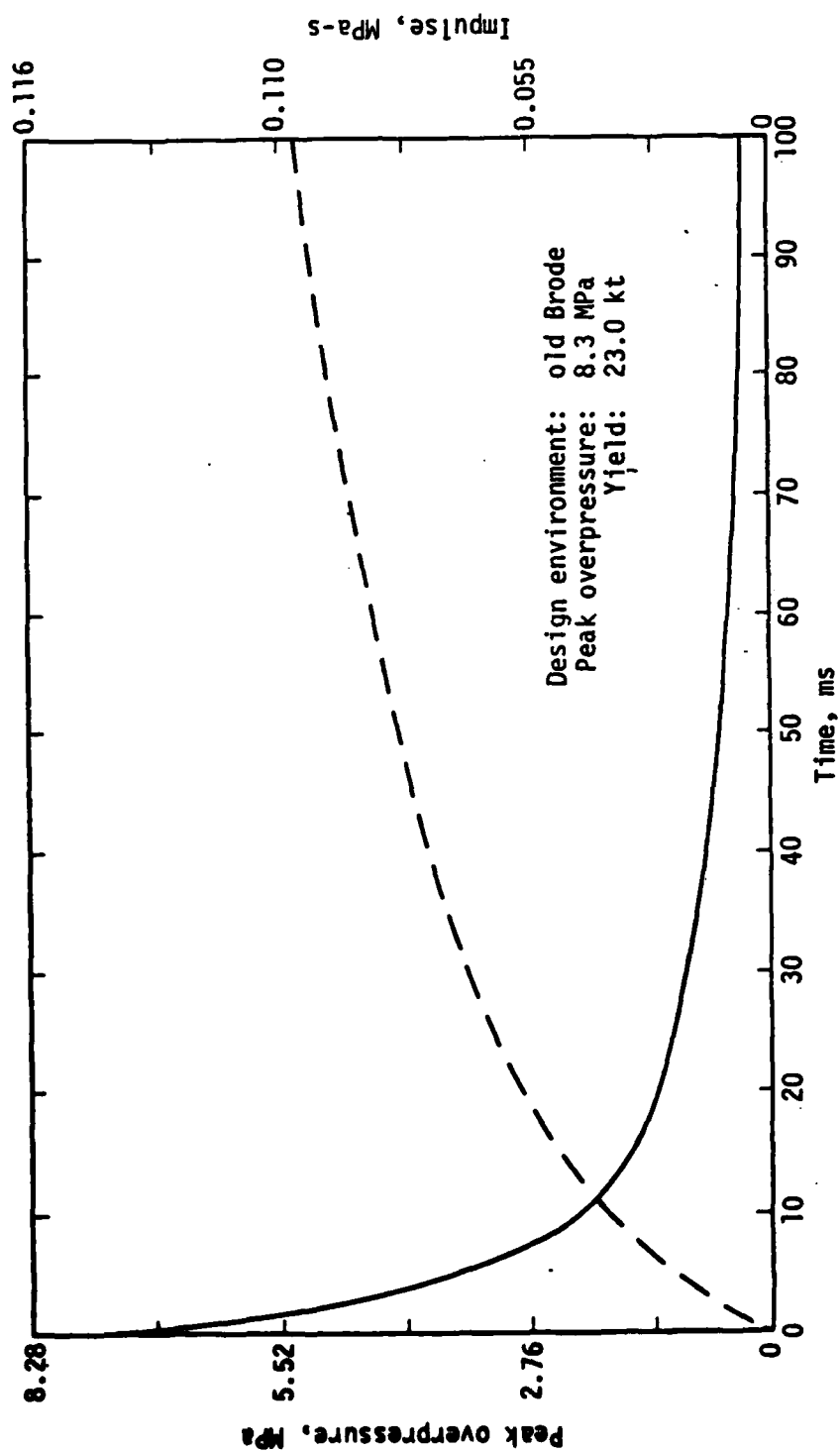
The models were seated in the test-bed at the proper depths. In the GOVS-3 test, the model was carefully seated in a grout solution directly on the bottom of the facility. Instrumentation cables entered the model through 50-mm-diameter holes spaced along the length of the model, and were protected by an encasement of polyvinylchloride (PVC) pipe near the entrance holes. At each instrumentation level the cables were routed horizontally to the wall of the facility, down the side, and then out through the cable exit ports.

When the sand-raining, the free-field instrumentation placement, and the structural gage placement had been completed, the closure was bolted to the model with eight 13-mm-diameter bolts torqued to approximately 200 N-m. Preparations for the placement of the explosive charge were now complete.

TEST ENVIRONMENT

The required environment for the GOVS test events was a vertical airblast having a peak overpressure of 8.3 MPa and a scaled yield of 23 kt (scaled 5 Mt) with a simulation time of 12.5 ms. The scaled Brode pressure-history and impulse curves for the desired environment are plotted in Figure 5. A HEST structure (Reference 7) was used to generate the environment. A modified form of the Lock-up Impulse Code (Reference 7) developed for the HP 9820 programmable calculator was used in the initial design of the HEST.

Because experimental data on the performance of the foam-cavity HEST in a confined environment were unavailable, three calibration tests were



conducted to define the HEST. The final design of the HEST used in the GOVS test events consisted of a 100-percent foam-filled cavity, 140 mm high. Four layers of 13.7-gr/mm detonating cord were evenly distributed throughout the cavity. The charge density of the explosives was 14.7 kg/m³; the total weight of the explosives was 48.8 kg. A single-point detonation scheme at the center of the HEST was used to ignite the system.

Approximately 300 mm of sand was rained in above the HEST as a base for the soil surcharge. The surcharge, which consisted of McCormick Ranch soil, was dropped into the facility. The total height of the overburden, sand and surcharge, was 2.29 m. Its density was 1326 kg/m³ and its total weight was 71,823 kg.

PRETEST PREDICTIONS

A SAMSON dynamic finite-element computer code (Reference 1) was used for the GOVS pretest predictions (References 3, 4, and 6). The SAMSON code was developed by the Illinois Institute of Technology Research Institute, and it was later modified and expanded by AFWL. The code is particularly suited for handling problems involving nonlinear material properties and a large number of degrees of freedom. It was designed specifically to investigate SMI problems.

The two-dimensional (2-D) model used for the GOVS SAMSON predictions consisted of the test structure, the sand test-bed, the wall of the GRABS facility, and the limestone along the side of and beneath the GRABS facility. Only a unit arc section of the test configuration was modeled because of the axial symmetry of the applied load and the symmetry of the test-bed. The centerline of the model was fixed radially, but was left

free to translate vertically. The exterior-boundaries of the model were totally fixed.

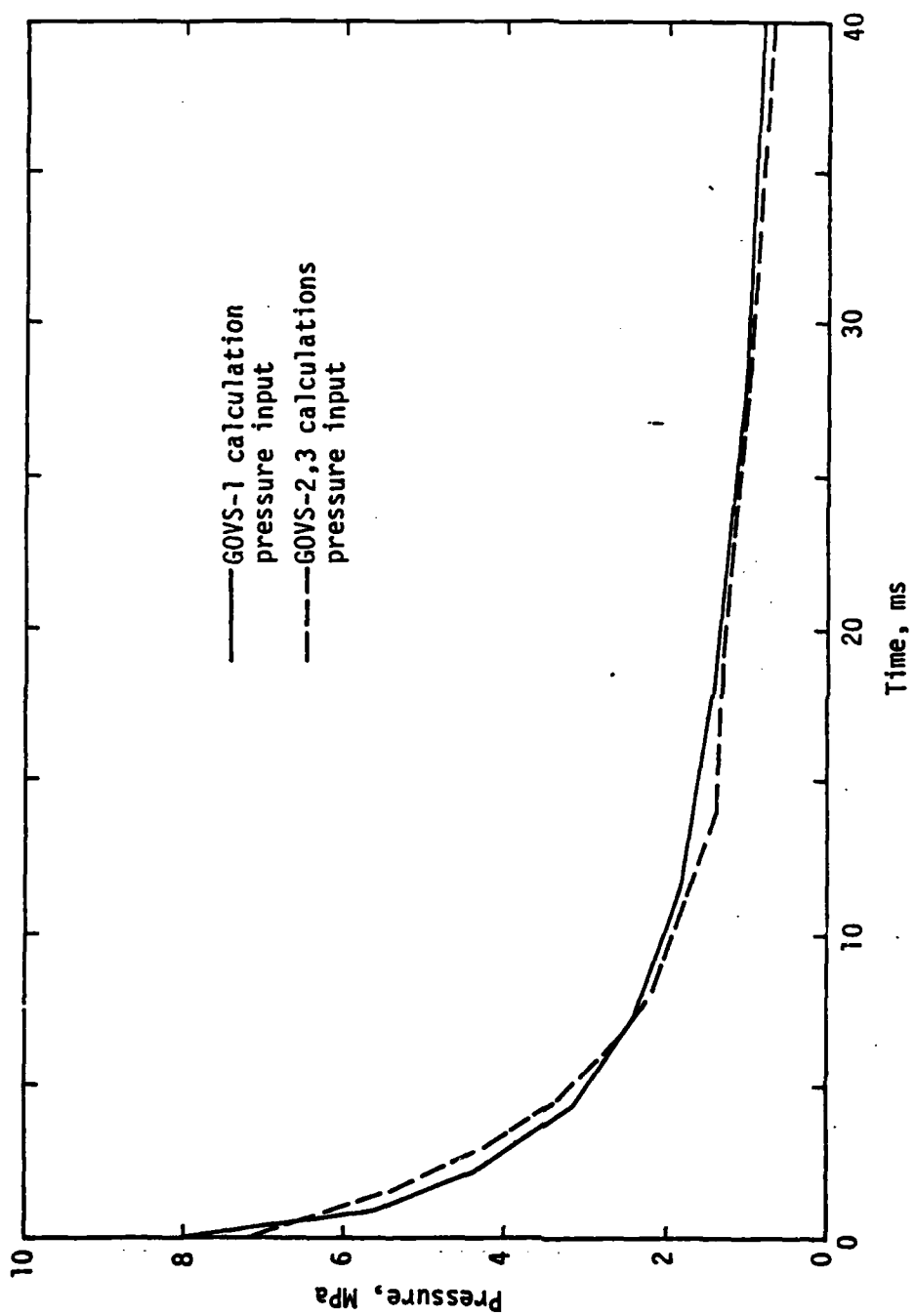
Sliding-separating boundaries were used in the meshes to model the interfaces between the sand and the test structure and between the sand and the liner of the GRABS facility. The sliding phenomenon is characterized in the SAMSON code by the Coulomb friction law and is limited to small displacement behavior.

The surface of the test-bed in the finite-element model was loaded with a double exponential fit to an average pressure history generated from the third calibration shot for the GOVS-1 calculation. The pressure history used for the GOVS-2 and GOVS-3 calculations was a double exponential fit to an average of the GOVS-1 data. The environments used in the calculations are shown in Figure 6. For input into SAMSON, this pressure history was approximated as a series of linear segments. The pressure was applied as a sweeping wave traveling from the centerline of the test-bed to the wall of the GRABS facility. A traveling wave was used in the calculation to simulate the conditions of a single centerpoint HEST detonation.

On the basis of the calculations, the following predictions were made:

GOVS-1

1. The entire shelter would translate as a rigid body, with an average peak vertical velocity of 6 m/s to 8 m/s and a permanent downward displacement of approximately 100 mm.
2. The closure would permanently deform downward at its center, with tensile cracking of the concrete occurring in the bottom at the center.



3. The concrete below the closure bearing would undergo limited plastic deformation.
4. The concrete wall of the tube would be severely distressed immediately below the transition, with extensive concrete cracking and buckling of the reinforcing steel occurring over at least a 0.3-m-length of the tube.

GOVS-2 (Results of the GOVS-1 test were considered in the GOVS-2 predictions.)

1. The entire shelter would translate as a rigid body, with an average peak velocity of 5 m/s to 6 m/s and a permanent downward displacement of approximately 70 mm.
2. The closure would displace downward but remain elastic.
3. The concrete below the closure would also remain elastic.
4. The concrete wall of the tube would remain elastic, and the primary response would be axial compression.
5. The base would undergo bending, which would be minimally transmitted to the wall.

GOVS-3 (Results of the GOVS-1 and GOVS-2 tests were considered in the GOVS-3 predictions.)

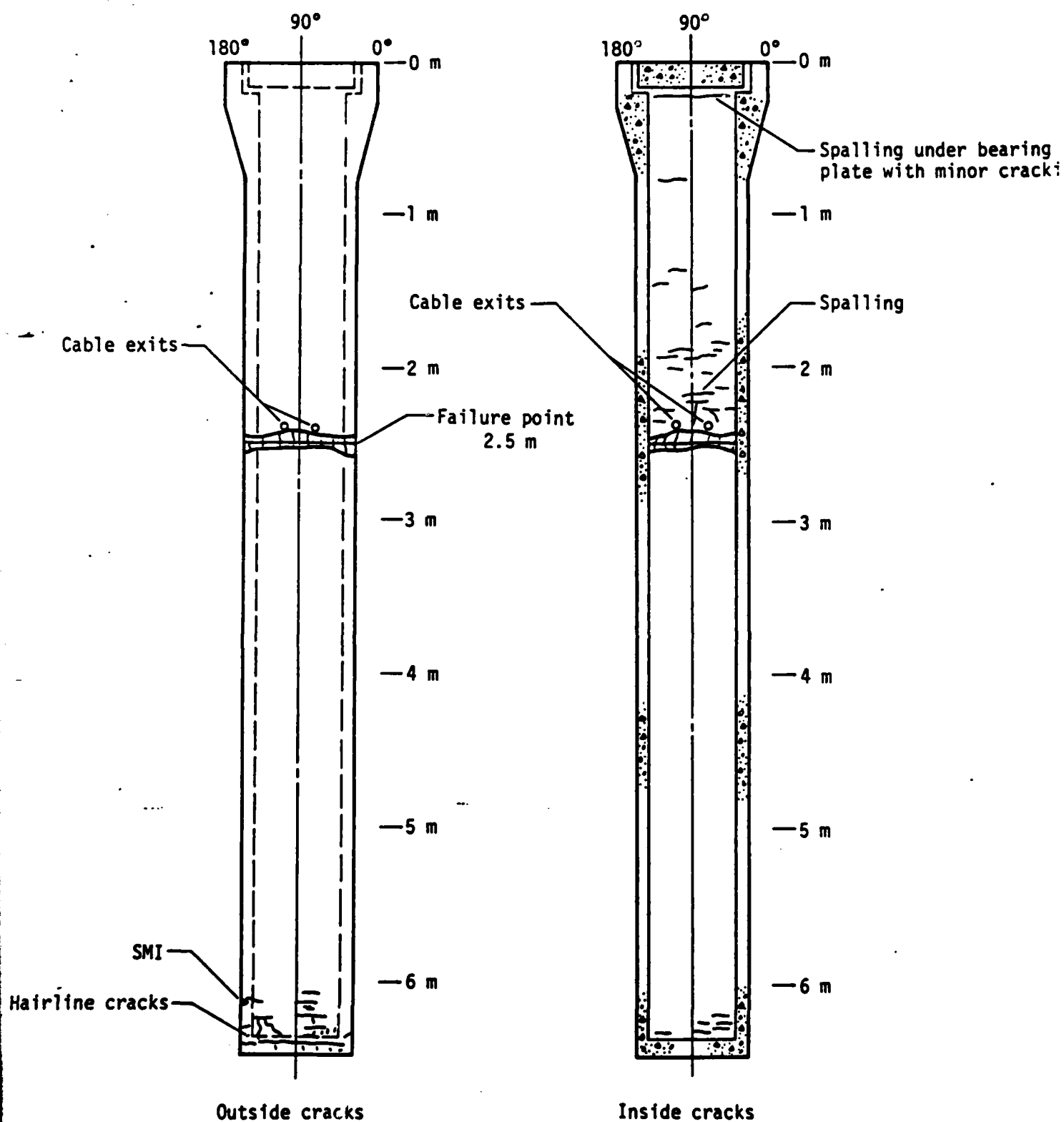
1. The closure would displace downward but would remain elastic.
2. The primary response of the structure would be axial compression, and the structure would remain in the elastic region.
3. The base would undergo slight bending but would remain elastic.
4. Possible areas of distress would include:
 - a. The bearing area of the structure, where crushing of the concrete might occur.
 - b. The intersection of the base and the wall of the structure, where high compressive stresses might develop.

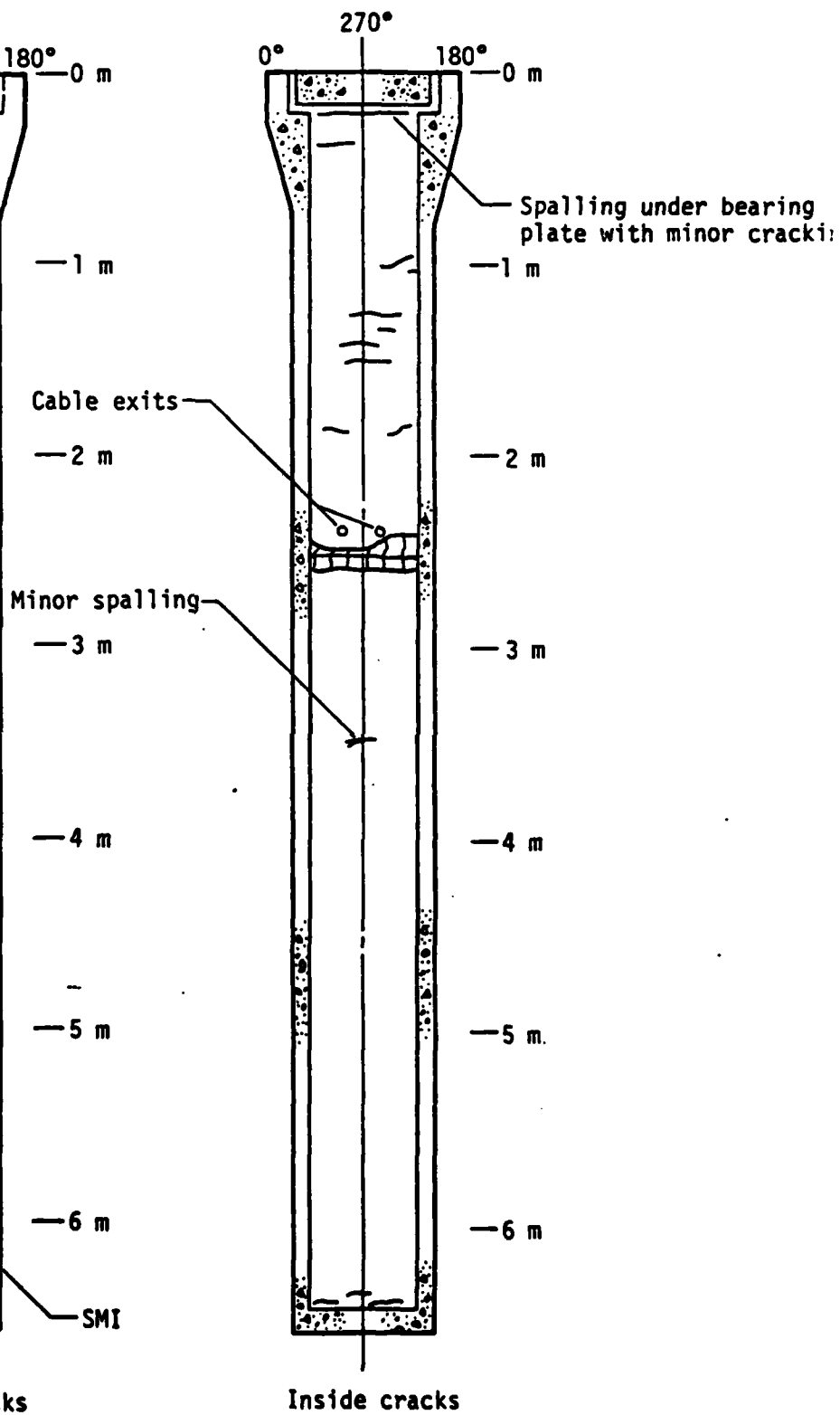
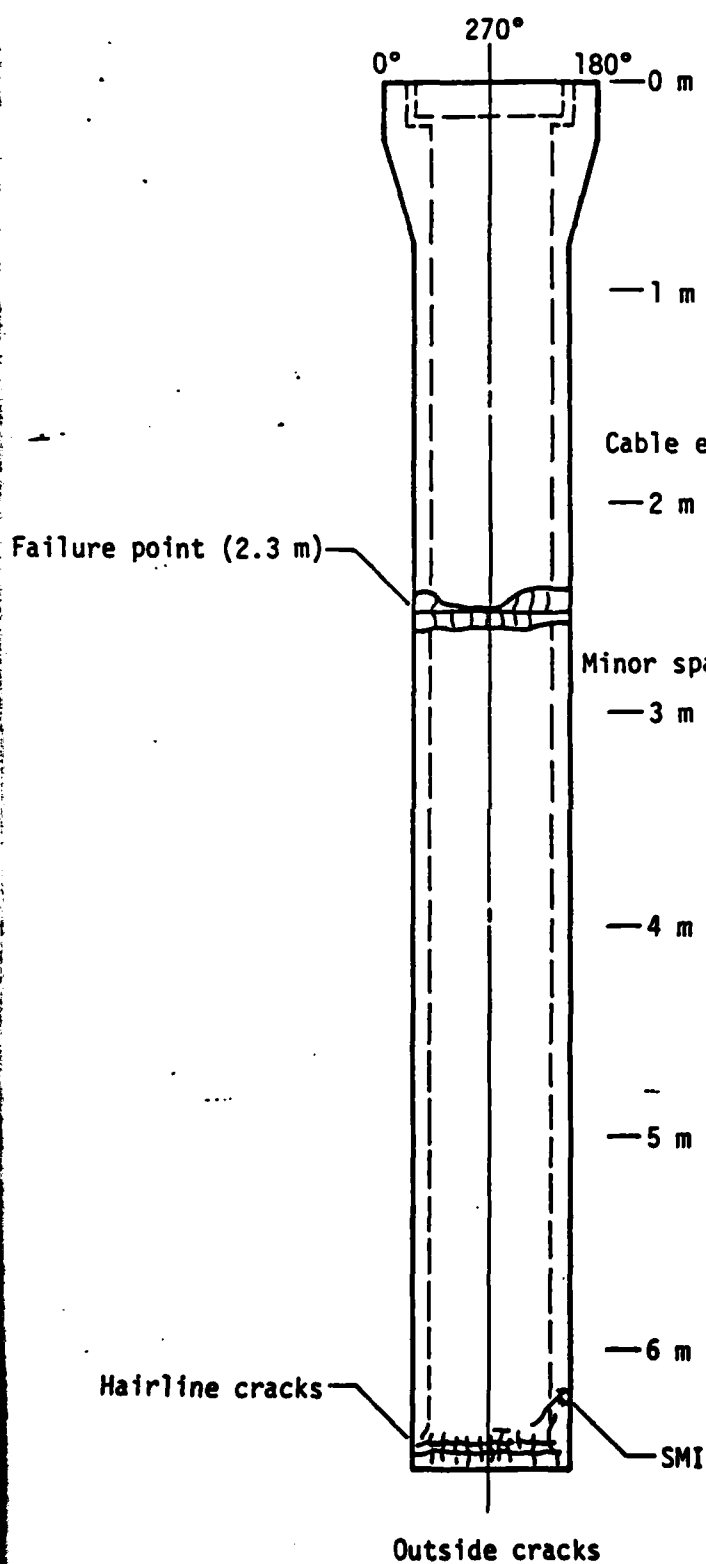
TEST RESULTS

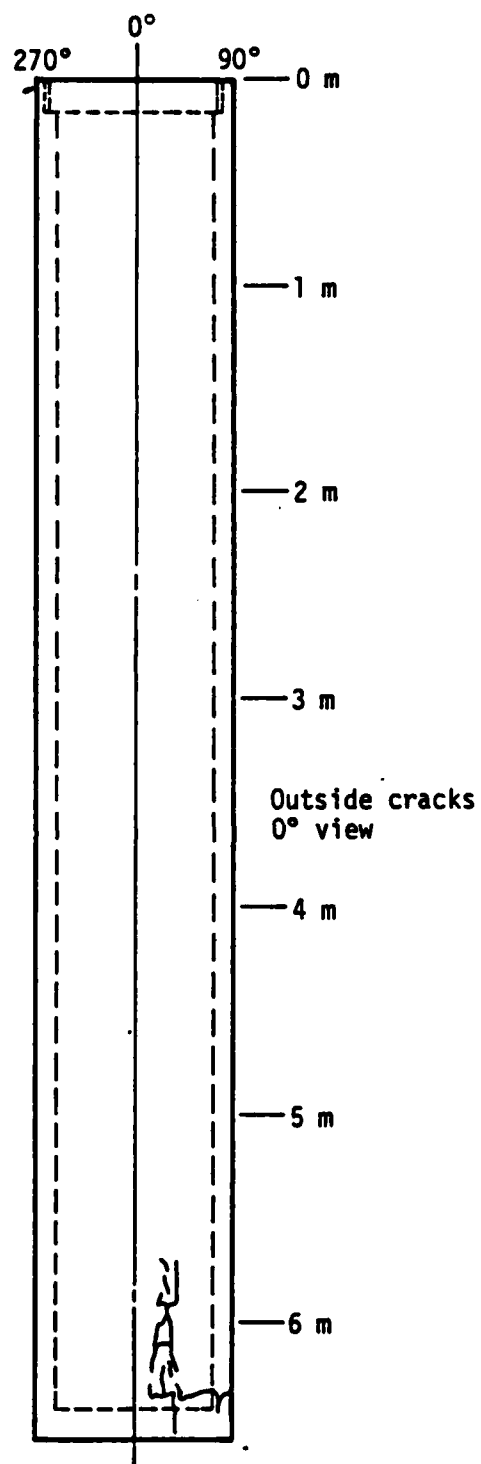
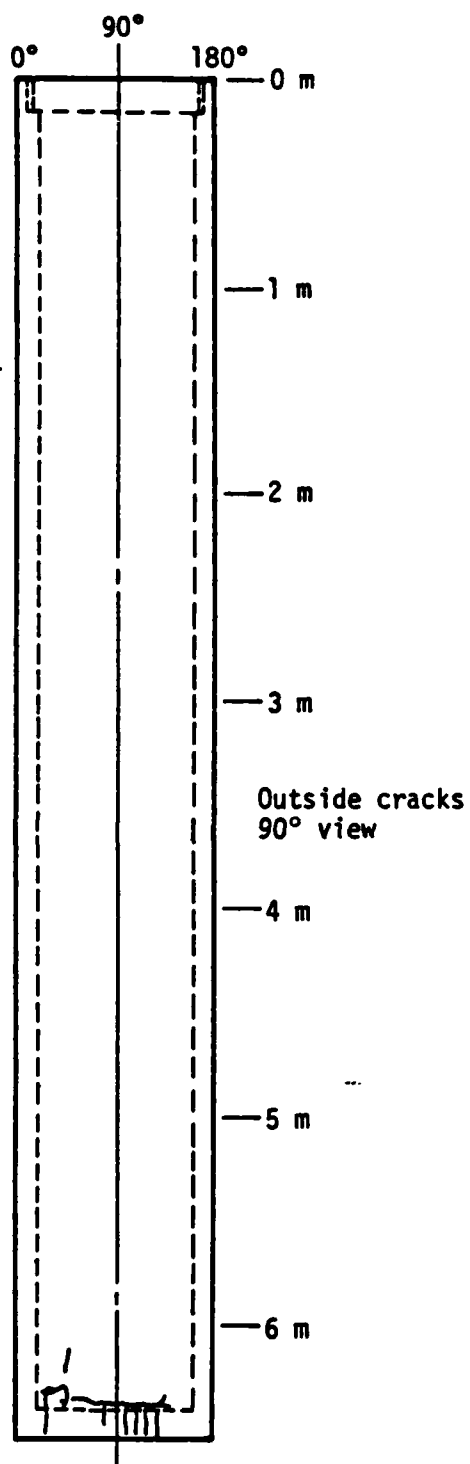
The GOVS-1 test structure experienced significant distress in the tube and base. Several circumferential compression cracks were observed in the top portion of the tube, and a major compression failure occurred in the tube wall at the 2.5-m elevation, as shown in Figure 7. The strain-gage data from this region indicated that the distress had been caused by the direct airblast loading of the structure. The base of the structure experienced toroidal bending, and tension cracks developed in the bottom of the tube and in the top surface of the base.

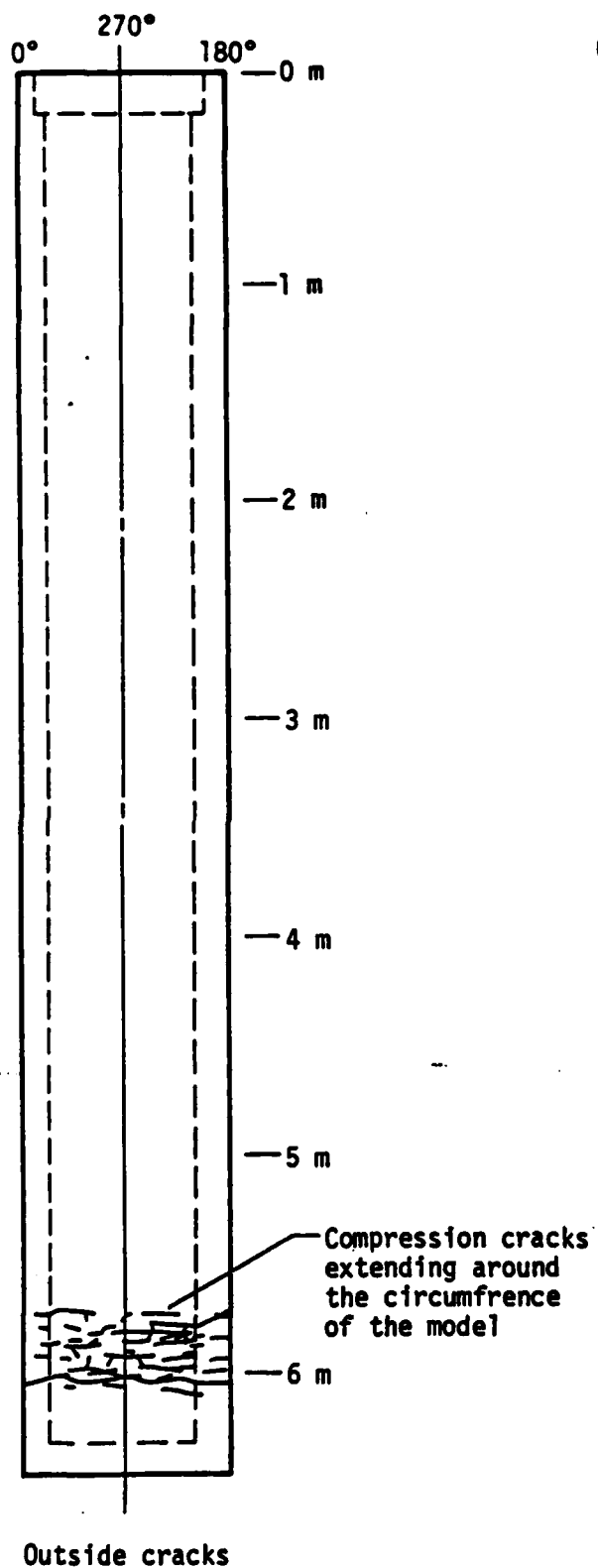
Unlike the GOVS-1 model, the GOVS-2 model did not fail under the airblast loading. However, the structure did experience minimal distress in the tube section at a depth of approximately 6.35 m. At this location, circumferential compression cracks and longitudinal tension cracks were observed on the outside wall of the structure around 75 percent of the circumference, as depicted in Figure 7. Circumferential-strain gage data from this region indicated that the distress was a result of toroidal bending of the tube wall at the base.

The GOVS-3 test structure experienced significant distress in the tube section at a depth of 6 m, where circumferential compression cracks were observed on both the inside and outside faces of the model wall and around its entire circumference, as shown in Figure 7. Larger cracks exposing buckled reinforcing bars on the inside face of the wall indicated that toroidal bending of the tube section had occurred at this location. It is apparent from the test data that the failure was not caused by direct airblast loading but by a combination of shear loading at the soil-structure interface and a shock wave reflected from the base of the model.

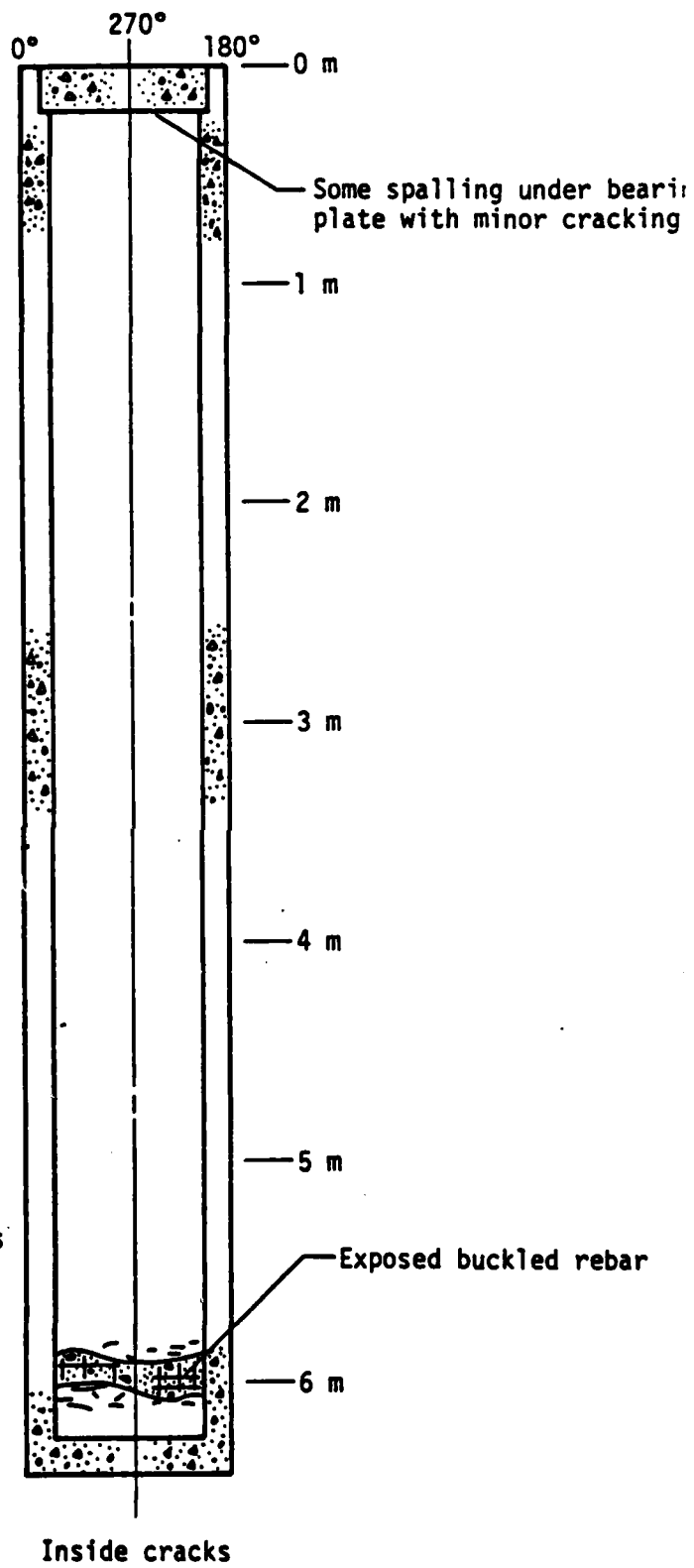








Outside cracks



Inside cracks

CONCLUSIONS

The GOVS test series provided data that were used to investigate the effects of variations in the structural details of the shelter models and in site geology on the response of a vertical shelter to airblast loading. The effects of varying structural details were evaluated by a comparison of the GOVS-1 and GOVS-2 test results. The effects of varying structure-to-bedrock depth were evaluated by a comparison of the GOVS-2 and GOVS-3 test data. The test data were also compared to pretest predictions made by a 2-D SAMSON dynamic finite-element computer code for the purpose of evaluating the predictions.

When the GOVS-1 and GOVS-2 test results are compared, it is apparent that the lower strength of the concrete in the GOVS-1 model and the presence of the shelter transition section (with the correspondingly lower t/r ratio of the tube section) had adverse effects on the response of the GOVS-1 model. The GOVS-1 model experienced significant distress in the tube and base, whereas the GOVS-2 model experienced only minimal distress in the tube section near the base. It can be concluded that the variations in structural detail affected the response of the models as follows:

1. The headworks and transition region of the GOVS-1 model flexed considerably more toward the interior of the structure than did that of the stiffer GOVS-2 model.
2. The initial peak strain at the top of the tube in the GOVS-1 model exceeded that of the GOVS-2 model because of the reduced cross-sectional area and lower strength of the concrete in the former.
3. The GOVS-1 tube section, with its lower t/r ratio, deflected more

radially inward than did the GOVS-2 tube section.

4. The behavior of the bases of the models was similar. Toroidal bending of the structure wall in this region was evident in both models. This bending, however, was much more pronounced in the GOVS-1 model with its thinner wall and less stiff concrete.

The effect of placing the vertical shelter directly on bedrock was evaluated by a comparison of the GOVS-2 and GOVS-3 tests. In both tests, the predominant model response was axial compression. In the GOVS-3 test, however, a shock reflection from the bedrock magnified the tube stresses and strains in the region of the base of the structure. The stresses and strains caused by this reflection produced severe distress in the base of the GOVS-3 model. Because the two tests were similar in every detail except depth to bedrock, it can be concluded that it is not desirable to place a shelter directly on bedrock.

The pretest calculations and predictions performed by the SAMSON dynamic finite-element computer code were in good agreement with the test data. The calculations for the first two tests accurately predicted the overall response of the structures. However, discrepancies between the predicted and the measured timing of the free-field soil stresses and magnitude of the interface normal and shear stress indicated that the material model for the soil and the friction coefficients at the soil-structure interface should be modified. Consequently, these parameters were modified for the GOVS-3 calculation, and when the predicted and the test data for the GOVS-3 were compared, it was concluded that the modifications had adequately corrected the irregularities found in the previous calculations. However, uncertainties associated with the accurate

modeling of the behavior of the soil-structure interface invite further study.

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Landon, Gary E., Narain, Ian G., and Stephens, Jerry E., "Giant Reusable Airblast Simulator (GRABS) on Vertical Shelters (GOVS)", *AFWL-TR-80-157*, Final Report to Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, November 1980.

- Figure 1. Detail definition for GOVS models
- Figure 2. Instrumentation layout for GOVS shelter models (1 of 3)
- Figure 2. GOVS-1 GOVS-2 test-bed instrumentation layout (2 of 3)
- Figure 2. GOVS-3 test-bed instrumentation layout (3 of 3)
- Figure 3. Location of GOVS models in GRABS facility
- Figure 4. Sand-raining device
- Figure 5. Pressure and impulse curves for GOVS test environment
- Figure 6. Pressure history for GOVS calculations
- Figure 7. Cracks in GOVS-1 shelter model A, 90-day view (1 of 4)
- Figure 7. Cracks in GOVS-1 shelter model A, 270-deg view (2 of 4)
- Figure 7. Cracks in GOVS-2 shelter model B (3 of 4)
- Figure 7. Cracks in GOVS-3 shelter model B (4 of 4)

SUMMARY: Protective Vertical Shelters, by Ian G. Narain, Jerry E. Stephens and Gary E. Landon. The GOVS test program, consisting of three tests on Missile-X (MX) vertical shelters, was concerned with the effects of site geology and structural detail on shelter response. Pretest calculations were performed for each test.

KEY WORDS: Axisymmetric model; Dynamic response; Giant reusable airblast simulator (GRABS); GRABS on vertical shelters (GOVS); Structure-media interaction; Missile-X (MX); Reinforced concrete; Shelter configuration; Vertical airblast; Vertical shelters

ABSTRACT: The response of buried vertical MX shelters to vertical airblast and to airblast-induced ground-shock loadings is examined. Three tests were conducted on 1/6 scale reinforced concrete models to investigate the effects of site geology and structural detail on shelter response. The experimental data provided an insight into shelter response, and was also used to evaluate the accuracy of pretest calculations and predictions.